

Radiation tolerance of FPCCD vertex detector for the ILC

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Abstract

The Fine Pixel CCD (FPCCD) is one of the candidate sensor technologies for the ILC vertex detector. The vertex detector is located near the interaction point, thus high radiation tolerance is required. Charge transfer efficiency of CCD is degraded by radiation damage which makes traps in pixels. We measured charge transfer inefficiency (CTI) of a neutron irradiated FPCCD prototype. We observed a degradation of CTI compared with non-irradiated CCD. To improve the CTI of irradiated CCD, we performed the fat-zero charge injection to fill the traps. In this paper, we report a status of CTI improvement.

1 Introduction

The main role of a vertex detector in ILC is to identify b-quark and c-quark from light quarks and gluons. In general, a b-jet has 3 vertices and c-jet has 2 vertices, while light quarks and gluons have 1 vertex. A vertex detector uses that information to identify quarks. Since lifetime of b-quark and c-quark is very short with about 1 pico second, the requirement for the impact parameter resolution is $5 \oplus 10/(p\beta \sin^{3/2} \theta) \mu\text{m}$ [1]. The innermost layer is located at radius of 1.6 cm from the beamline for good impact parameter resolution, thus it is exposed to many e^+e^- backgrounds from beam-beam interaction. Hit occupancy less than a few % is necessary for track reconstruction but it would be about 10 % using a vertex detector which has normal pixel size $25\mu\text{m} \times 25\mu\text{m}$ when it accumulates all the hits from one beam train.

There are two solutions to get a low pixel occupancy. One is to read out many times in one beam train. Its problem is a EMI noise from beam. Another is to use a small pixel size as $5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$ and to read out during the train gap. In this way, there are no EMI noise. The Fine Pixel CCD (FPCCD) vertex detector adopts the second way [2].

2 Radiation damage to the FPCCD

The vertex detector is located near the interaction point, thus it will be exposed much radiation. There are two main radiation which is written as follows.

1. Pair background from beam-beam interaction
2. Neutrons from beam dump

Pair background is electron positron pairs created by beam-beam interaction and it is much generated around interaction point. Hit rate of pair background is simulated as $6.32\text{ hits/cm}^2/\text{BX}$ at 1.6 cm from interaction point at 500 GeV . Operation time of ILC is planned as $1.0 \times 10^7\text{ sec}$ and it is shared by ILD and SiD, thus the vertex detector will be used for $0.5 \times 10^7\text{ sec}$ in one year. One train consists of 1312 bunches and it collides 5 times in 1 second so that number of hits by pair background in one year is estimated as $2.07 \times 10^{11}\text{ e/cm}^2/\text{year}$. Fluence of neutrons from beam dump is estimated as $9.25 \times 10^8\text{ 1MeVn}_{\text{eq}}/\text{cm}^2/\text{year}$ [3].

These radiations cause damage to the silicon devices and the damages are classified as bulk damage and surface damage. Bulk damage is caused by displacement of silicon atoms. It makes lattice defects which influence the performance of FPCCD. Damage of this effect is represented by Non ionizing energy loss (NIEL) which is energy loss of radiation used for bulk damage. Surface damage is caused by ionization in the silicon dioxide.

One of the important aspects of performance of CCD sensors is charge transfer inefficiency (CTI) which shows charge loss during charge transfer. This is caused by lattice defect, thus NIEL should be considered. We introduced NIEL hypothesis that bulk damage of semiconductor is proportional to NIEL. NIEL damage for a 30 MeV electron is factor 16 smaller than that for an 1 MeV neutron, thus NIEL damage for pair background in ILC is $1.29 \times 10^{10}\text{ 1MeVn}_{\text{eq}}/\text{cm}^2/\text{year}$ [4] [5]. If we suppose 3 years operation and safety factor 3, $1.24 \times 10^{11}\text{ 1MeVn}_{\text{eq}}/\text{cm}^2$ is required for bulk damage from pair background and neutrons.

2.1 Charge transfer inefficiency

Charge transfer inefficiency (CTI) is introduced as an indicator of the charge loss. We defined CTI as inefficiency of one transfer from pixel to pixel and expressed as below formula.

$$Q_n = Q_0(1 - CTI)^n \quad (1)$$

where Q_0 is signal charge before transfer and Q_n is signal charge after n times transfer.

3 Neutron irradiation test

A neutron irradiation test was performed at CYRIC of Tohoku University from 15th to 17th Oct. 2014. The energy of neutron beam produced by 70 MeV proton beam through a reaction of $Li + p \rightarrow Be + n$ is about 65 MeV [6]. A FPCCD prototype whose pixel size is $6\mu\text{m} \times 6\mu\text{m}$ was irradiated 2 hours and its fluence was $1.78 \times 10^{10} \text{ n}_{\text{eq}}/\text{cm}^2$. In ILC experiment neutron fluence is estimated as $1.85 \times 10^9 \text{ n}_{\text{eq}}/\text{cm}^2/\text{year}$ thus the neutron fluence corresponds to 19 years of $\sqrt{s} = 500 \text{ GeV}$ ILC beam time shared by two detectors. Comparing to requirement for radiation tolerance to neutron and pair background combined in ILC experiment, this fluence is 7 times smaller.

4 CTI performance of irradiated FPCCD

4.1 Measurement of CTI

Irradiation by 5.9 keV X-ray from Fe55 is used to measure CTI. Signal charge from Fe55 in each pixel is fitted with a function of $f(x, y) = S(1 - CTI_h)^x(1 - CTI_v)^y$ where S is signal charge of X-ray from Fe55 before the transfers then CTI is obtained (Fig.1). Signals are transferred horizontally and vertically, and CTI is defined for each case: CTI_h and CTI_v . In this study we used super pixels each of which consists of 16×16 pixels instead of pixels because of low statics of X-ray. The CTI's after the irradiation were found as follows: $CTI_h = (5.93 \pm 0.05) \times 10^{-5}$ and $CTI_v = (7.32 \pm 0.22) \times 10^{-5}$.

4.2 Requirement for CTI

CTI is an indicator of charge loss, thus large CTI means small signal charge and S/N ratio gets worse. Considering the smallest signal in ILC experiment, we suppose a minimum ionizing particle (MIP) passing through a pixel. A MIP generates 80 electrons per $1\mu\text{m}$ in silicon. Pixel size of the FPCCD is $5\mu\text{m} \times 5\mu\text{m} \times 15\mu\text{m}$ and number of electrons generated by MIP is different depending on direction of an incident particle. Shortest path length is $5\mu\text{m}$ and number of generated electrons is 400 which is the smallest signal. Signal charge is lost by trap so that charge loss term $(1 - CTI)^n$ is added, where n is number of transfers and it is 11000 in the FPCCD used in ILC. Noise corresponding to the width of dark current is 42 electrons. S/N ratio can be written as follows.

$$S/N = \frac{(1 - CTI)^{11000} \times 400}{42} \quad (2)$$

Relation between S/N ratio and the required CTI is showed in Fig.2. After irradiation, $CTI_h = 5.93 \times 10^{-5}$. As discussed in Section 3, it will become 7

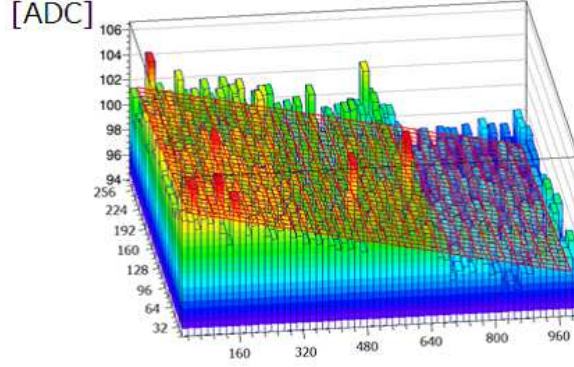


Figure 1: Two dimensional distribution of the peak position (ADC count) of 5.9 keV X-ray from Fe55. X and Y axes are horizontal and vertical numbers for pixel. Readout located at (0,0). The distribution was fitted with the function described in the text.

times worse in the real ILC experiment when we assume that CTI gets worse in proportion to radiation dose; $CTI_h = 41.5 \times 10^{-5}$. Putting this CTI to Eq. 2, S/N ratio is 0.1 which is not good and should be improved. When we suppose that a goal of S/N ratio is 10, CTI should be less than 2.45×10^{-5} .

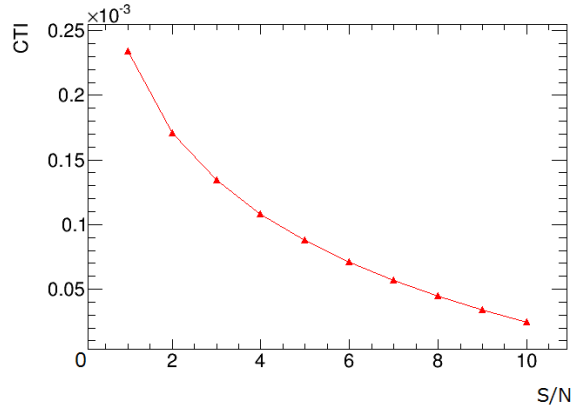


Figure 2: Relation between S/N ratio and the required CTI.

5 CTI improvement

Charge loss is caused by trap of signal charge in lattice defects. It can be avoided by filling up the lattice defects by additional charge. This method is

called fat-zero charge injection.

In this study, fat-zero charge is injected by using LED. Light from LED is irradiated to prototype FPCCD uniformly, thus charge is also generated uniformly.

5.1 Result

CTI was measured in same way as the no fat-zero charge case. The CTI's with 600 electrons injected were found as follows: $CTI_h = (6.75 \pm 0.04) \times 10^{-6}$ and $CTI_v = (3.07 \pm 0.15) \times 10^{-5}$. This is factor 9 improvement for CTI_h and factor 2 improvement for CTI_v . Measured CTI as a function of fat-zero charge is shown in Fig. 3.

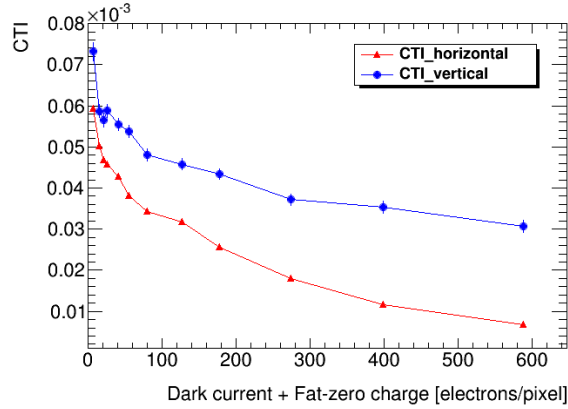


Figure 3: Measured CTI as a function of fat-zero charge.

5.2 Requirement for CTI with fat-zero charge

Fat-zero charge makes shot noise so that requirement for CTI gets strict. Shot noise is statistical deviation of number of electrons and follows Poisson statistics. Thus standard deviation is square root of number of electrons. Shot noise term is added to Eq.2, S/N ratio is expressed as follows.

$$S/N = \frac{(1 - CTI)^{11000} \times 400}{\sqrt{42^2 + N_{Fatzero}}} \quad (3)$$

where $N_{Fatzero}$ shows number of fat-zero charge. Relation between S/N ratio and CTI with and without fat-zero charge is shown in Fig.4. The measured CTI multiplied by factor 7 is also plotted for the fat-zero charge of 80, 120, 180, 280, 400 and 600 electrons. S/N ratio with 600 electrons injected is 4.9 and it is smaller than the goal. We have to consider about more improvement of CTI. In this set up, limit which came from readout circuit of fat zero charge is 600 electrons and more improvement by more injection of fat-zero charge is expected.

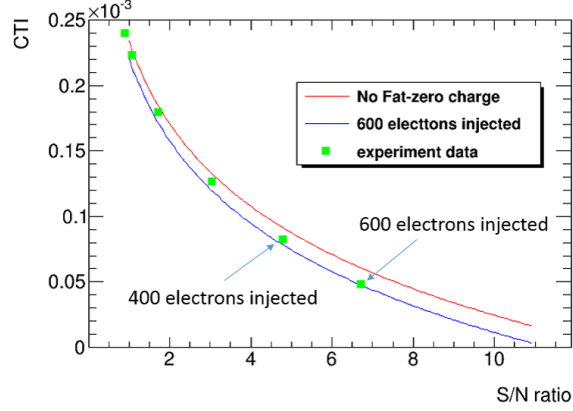


Figure 4: Relation between S/N ratio with fat-zero charge and required CTI. The measured CTI multiplied by factor 7 is also plotted for the fat-zero charge of 80, 120, 180, 280, 400 and 600 electrons.

5.3 Possible improvement

We have some possible plans to improve CTI.

5.3.1 Horizontal pixel size

Prototype FPCCD has 3 channels whose pixel size of horizontal shift registers is different. As a result of measurements, dependence of horizontal pixel size for fat-zero charge effects was observed and it is shown in Table 1.

Horizontal registers size	No fat-zero charge	600 electrons injected	Improvement
$6\mu\text{m} \times 12\mu\text{m}$	$CTI_h = 5.93 \times 10^{-5}$	$CTI_h = 0.68 \times 10^{-5}$	Factor 9
$6\mu\text{m} \times 18\mu\text{m}$	$CTI_h = 5.45 \times 10^{-5}$	$CTI_h = 1.05 \times 10^{-5}$	Factor 5
$6\mu\text{m} \times 24\mu\text{m}$	$CTI_h = 4.85 \times 10^{-5}$	$CTI_h = 1.89 \times 10^{-5}$	Factor 3

Table 1: Relation between horizontal pixel size and improvement of CTI_h

Maximum improvement was achieved in smallest pixel and minimum improvement was achieved in largest pixel. The improvement of CTI by fat-zero charge injection is more effective in small horizontal pixels.

5.3.2 Notch channel

Notch channel is narrow channel in the potential well and it is produced by additional implant. When signal charge is transferred in notch channel, it encounters less lattice defects than normal CCD and number of trap is decreased. Thus it can achieve CTI improvement.

5.3.3 Annealing

Recovery of CTI from annealing is reported [7]. This is because lattice defects is repaired by heat. CTI can be improved by 2 or 3 times after 168 hours at 100 degree annealing.

5.3.4 Noise reduction

Requirement for CTI can be relaxed by noise reduction. Noise consists of fixed pattern noise which is different from dark current of each pixel, shot noise and readout noise from circuit. Fixed pattern noise and shot noise is caused by dark current, however dark current is a few electrons so that it is difficult to reduce fixed pattern noise and shot noise. We can improve readout noise.

6 Summary

We performed neutron beam test for FPCCD. CTI degradation is observed and it is crucial damage when we assume 3 years operation, safety factor 3 and scaling neutron fluence to expected radiation damage in ILC. However it can be improved by fat-zero charge injection. Factor 9 improvement for horizontal CTI and factor 2 improvement for vertical CTI were achieved.

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